VSB – TECHNICAL UNIVERSITY OF OSTRAVA
Faculty of Mechanical Engineering
Department of Energy Engineering

DIPLOMA THESIS

Design of Piston Compressor Coolers
Návrh chladičů pro pístový kompresor

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VŠB - Technical University of Ostrava
Faculty of Mechanical Engineering
Department of Energy Engineering

Diploma Thesis Assignment

Student:	**Sivakumar Vetrivelavan, BE**
Study Programme:	N2301 Mechanical Engineering
Study Branch:	2302T006 Energy Engineering
Title:	Design of Piston Compressor Coolers Návrh chladičů pro pístový kompresor
The thesis language:	English

Description:

Prepare a study on the cooling of multi-stage piston compressors and design the construction and size of coolers for the 1TSK 115 piston compressor located in G315 laboratory. It is a single-cylinder three-stage standing compressor with the following parameters:
Suction air pressure: 0.1 MPa,
Discharge air pressure: 20 MPa,
Suction air temperature: 20 °C,
Compressor performance: 20 m^3/h,
Electromotor input: 5kW,
Rotations: 800 rpm.
Use the calculations of multistage compression to determine the dimensions of heat exchange surfaces of two coolers and an aftercooler and their sequences during compression. Create a wiring diagram including the necessary measurement points in order to determine the performance of the individual coolers and design their construction.

References:

[1] KUPPAN, T. Heat exchanger design handbook. 2nd ed. Boca Raton: CRC Press, c2013. ISBN 978-1-4398-4212-6.
[2] BLOCH, P., HEINZ, A. Practical Guide to Compressor Technology – Second Edition. New Jersey: John Wiley & Sons, 2006, 555 p. ISBN: 978-0-471-72793-4.
[4] MANISH, B. Compressors. Scitus Academics LLC, 2015, 322 p. ISBN: 978-1-681-17500-3.
[3] JÍLEK M.: Thermomechanics. ČVUT 2002, ISBN 80-01-02077-0
[4]http://www.academia.edu/5223501/A_STUDY_BASED_ON_DESIGN_OF_AIR_COMPRESSOR_INTERCOOLER
[5] Websites of Measuring Equipments Producers

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

Supervisor: **Ing. Tomáš Výtisk, Ph.D.**

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ANNOTATION OF DIPLOMA THESIS

SIVAKUMAR VETRIVELAVAN. Design of Piston Compressor coolers 1TSK 115: Master thesis. Ostrava: VŠB–Technical University of Ostrava, Faculty of Mechanical Engineering, Department of Energy Engineering, 2019, 56 p.
Thesis head: Ing. Tomáš Výtisk, Ph.D.

The Diploma thesis is deals with Design of coolers for three stage piston compressor. The first part of the thesis is deals with compressor and its types, piston compressor, its components and working principle. The following chapter deals with coolers, types of coolers and measurement of flow parameters. In the practical part a new concept of design is obtained and designed using solid works v5 software and successive calculation for dimensions of the cooler for selected piston compressor is calculated. On the basis of verification with the thesis supervisor the design of cooler is further done. The newly designed cooler is documented in the enclosure of this diploma thesis.

Keywords: Piston compressor, Intercooler, Aftercooler, Flow measurements, Dimensions of the heat exchanger.

ANOTACE DIPLOMOVÁ PRÁCE

SIVAKUMAR VETRIVELAVAN. Návrh chladičů pro pístový kompresor 1TSK 115: Diplomová práce. Ostrava: Vysoká škola báňská - Technická univerzita Ostrava, Fakulta strojní, Katedra energetiky, 2019, 56 s. Vedoucí práce: Ing. Tomáš Výtisk, Ph.D.

Diplomová práce se zabývá návrhem chladičů pro třístupňový pístový kompresor. První část práce se zabývá kompresory a jejich rozdělením, pístovým kompresorem, jeho součástmi a principem práce. Následující kapitola se zabývá chladiči, typy chladičů a měřením průtoků. V praktické části je předložena nová koncepce výměníku, navržena pomocí prací v5 software a postupně jsou vypočítány rozměry chladiče pro vybraný pístový kompresor. Na základě konzultací s vedoucím práce je dále zpracován návrh chladiče. Schéma nově navržených chladičů je uvedeno v závěrečné části této diplomové práce.

Klíčová slova: Pístový kompresor, mezichladič, dochlazovač, měření průtoku, rozměry výměníku tepla.

Table of contents

List of Figures

List of variables

Variables	Abbreviation	Units
C_P	Specific Heat capacity (isobaric)	J/kg*K
C_V	Specific Heat capacity (isochoric)	J/kg*K
d	Inner diameter	mm
D	Outer diameter	mm
P_{el}	Electromotor input	kW
K_1, K_2, K_3	Overall heat transfer coefficient	W/m*K
ln	Logarithmic mean	[-]
MTD	Mean temperature difference	°C
m_{air}, m_w	Mass of air flow, Mass of water flow	Kg/s
n	Polytropic exponent	[-]
Nu	Nusselt number	[-]
P, p^{γ}	Compressor Pressure, Adiabatic Pressure	MPa
Pr	Prandtl number	[-]
r	Rotations	rpm
R	Gas constant	J/kg*K
Re	Reynolds number	[-]
t	Temperature of the cooler	°C
T	Compressor Temperature	°C
V	Compressor Volume Flow	m^3/s
W	Work done	J/s
α_1, α_2	Heat transfer coefficient	W/m^2*K
ΔT	Change in temperature	°C
λ_{air}, λ_w	Thermal conductivity of air, water	W/m*K
η	Efficiency of Compressor	[-]
ρ	Density	kg/m^3
μ_{air}, μ_w	Dynamic viscosity of air, water	Pa*s
v_{air}, v_w	Velocity of air, water	m/s
γ	Adiabatic index or Heat capacity ratio	[-]

List of indexes

Indexes	Abbreviations
1	Inlet flow of first stage of compressor
2	Outlet flow from second stage of compressor
3	Outlet flow from third stage of compressor
4	Outlet flow from third stage of compressor
Cu	Copper
°C	Temperature in degree Celsius
Fe	Iron
°F	Temperature in Fahrenheit
K	Temperature in Kelvin

1. Introduction

My topic of the thesis is Design piston compressor coolers. The piston compressor 1TSK 115 is chosen which is located at Mechanical laboratory in VŠB–Technical University of Ostrava. It is a three-stage piston compressor in which at each stage the discharge air has to be cooled to increase the efficiency of compression work. My aim is to design water cooled coolers both intercooler and aftercooler which is used to cool the air at the end of every compression stage. The shape of the model is shell and tube type heat exchanger. Piston compressor is a reciprocating type of air compressor in which air is sucked inside a cylinder chamber and compressed with the help of reciprocating piston. It is also called as positive displacement compressor. My thesis has two parts first one is theoretical part and the second one is design and calculation part.

The theoretical part deals with brief description of compressor, types of compressor and piston compressor. Then description about coolers and its types, Intercooler, Aftercooler and shell and tube type heat exchanger. I also explained about measurement of flowmeters which are used measure pressure, temperature and air flow inside the compressor. A flowmeter instrument is selected for each flow parameter and the measurement is noted which is useful during design of coolers.

The calculation and design part deals with dimension calculation of heat exchanger and design of both intercooler and aftercooler. For each air flow and water flow inside the heat exchanger heat transfer coefficient α and overall heat transfer coefficient k is calculated which used to calculate dimensions and efficiency of heat exchangers. The new design model of heat exchanger (Intercooler and after cooler) is designed with calculated dimensions. I also proposed suitable material in the design which has high thermal conductivity for both air and water flow tube. It helps to increase the heat transfer inside the heat exchanger. At the end of the thesis I also added properties of air and water at calculated pressure and temperature inside the compressor.

2. Compressor [5]

Machines producing compressed air or any other compressed gas are called compressors. They are used not only in the production of gases, but also in their storage and storage transport. In the compressor, the energy exerted changes into the pressure energy of the working substances and partly in heat. Therefore, compressors are between driven and thermal machines. They prevail in the central production of air, which is distributed to individual equipment. Air compressors are the most common type used to compress the air. The thermodynamic process that takes place during compression of gas is called compression. Theoretically compression can be described by different thermodynamic processes - isentropic, isothermal and polytropic.

Compressors compress the gases to higher pressures. In general, for small pressure and large volume of compressed gases are preferably used by rotary compressors, high pressures and small volume of compressed gases are used by multi-stage piston compressors.

Piston compressors are designed for smaller gas volumes but compressed to hundreds of MPa. Their design and function are essentially similar to piston pumps, the differences during the work cycle are due to the fact that gases, unlike liquids are compressible. Low power piston compressors are single cylinder, for higher power double and multi cylinders are used. At high pressure ratio one-step compression is not possible. The gas is compressed several times, gradually and regularly with coolers before entering the next stage.

2.1 Types of compressor [14]

Compressors come in many different designs in order to handle a wide variety of process applications. The two most common compressor designs are positive displacement and dynamic. Positive displacement compressors include reciprocating and rotary units.

Positive displacement compressors work by continuously forcing gas into a smaller and smaller volume, using either a piston or tight-fitting rotors, and then expelling the reduced volume of gas into a discharge passageway.

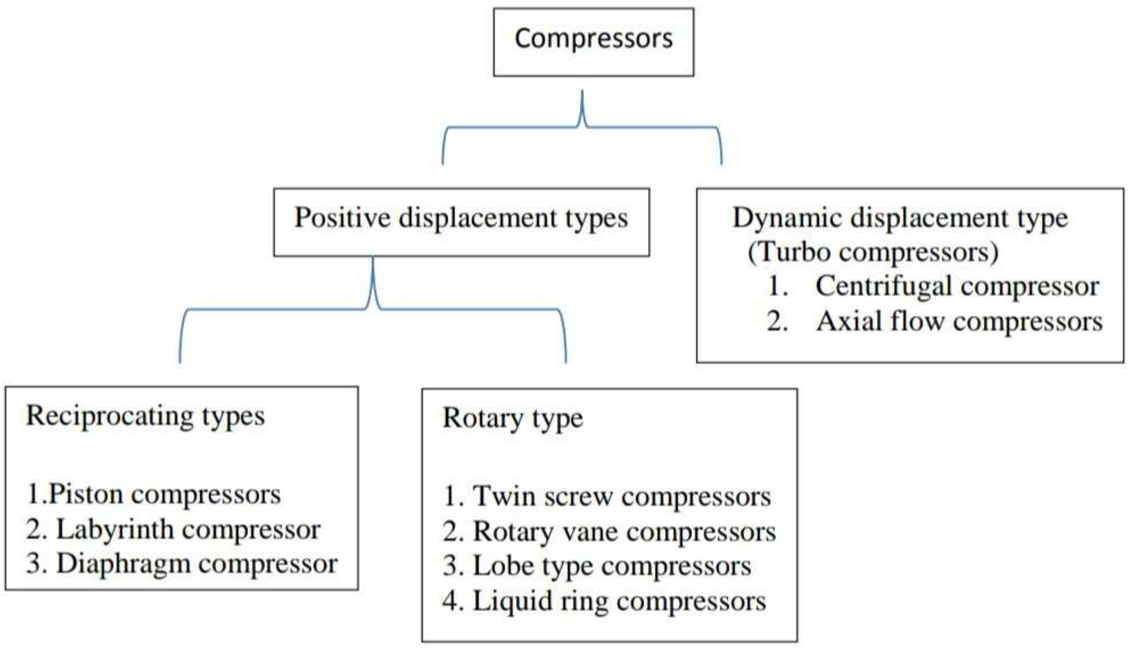

Figure 1. Types of compressor. [5]

2.1.1 Rotary compressors

Volume changes with piston or pistons that rotate about an axis parallel to the cylinder axis. They do not have valve manifolds; compression takes place with a constant (so-called "built-in") pressure ratio. Some of the types of rotary compressor is listed below.

2.1.1.1 Rotary vane compressors

It has a rotor eccentrically located in a cylindrical chamber. The blades inserted in the milled grooves of the rotor are pressed against the chamber walls by springs and centrifugal force. The space between the vane and the rotor decreases towards the discharge, thereby compressing the gas. Their working pressure is up to 0.5MPa, a multistage arrangement is required for higher compression levels. The advantage of this type is relatively simple construction and therefore high operational reliability.

2.1.1.2 Screw compressors

It achieves gas compression by reducing the volume of cavities between the screw rotors and the compressor housing. The rotors rotate in the opposite direction, thereby increasing the volume of cavities on the suction side and gradually decreasing on the discharge side. Gas transported in the pressure branch is gradually compressed as a result of the reduction in the volume of the cavities. The principle of operation is the same as for screw pumps.

Oil is injected into the compressor to seal the rotors and cool the compressed gas. Single-stage compressors achieve an overpressure up to 0.25 MPa in two-stage then up to 1 MPa.

2.1.1.3 Liquid ring compressor

At the periphery of the compressor casing, a liquid ring is formed by rotating the rotor to seal the space inside the rotor. It consists of blades attached to an eccentrically mounted rotor rotating clockwise. The gas is sucked on the lower left side of the compressor and extruded on the lower right side where the space between the blades and the liquid ring is significantly reduced, leading to gas compression. The rotary liquid ring compressor is suitable for large quantities of gas and overpressure up to 0.5 MPa.

2.1.2 Dynamic Compressor

Dynamic compressors are dependent on a fluid's momentum and inertia.

2.1.2.1 Centrifugal compressors

These are the machines where gas enters the suction nozzle axially into the hollow blades of the first circulating wheels. From the impeller, the gas is radially extruded into the diffuser where the gas is cooled and its flow rate is reduced to convert some of the kinetic energy into pressure energy. To the next stage, the diffuser gas is passed through the return ducts to the axis of the hollow impeller. In the last stage of diffuser compressed gas flows into the outlet port. This type of compressor has a relatively low compression ratio at the first stage and therefore multiple stages, at least three, are connected to one shaft. Rotor speed is typically between 5,000 and 12,000 rpm, and the outlet pressure typically does not exceed 2 MPa.

2.1.2.2 Axial-flow compressors

They accelerate the air flow in the impeller (rotor) blades and slow in its guide vanes (stator). One stage comprises a single ring of guide vanes movable and air enters the compressor axially, the guide vane gets higher speed, progressing to the stator, where its velocity slows and then proceeds to the next step. The space in which the gas is compressed, the length of the circulating and guide vanes decreases away from the suction into the discharge due to the reduction in the volume of the compressed gas as the pressure increases. Axial turbocharge compressors compress large volumes to a discharge pressure of up to 1 MPa.

2.1.2.3 Turbocharge compressors

In this compression takes place by accelerating the gas and then slowing it down when the kinetic energy of the gas is converted into pressure energy (Bernoulli principle). This transformation takes place in the active part of the machine in the case of radial compressors it occurs at the impeller and the diffuser placed behind it, in the axial compressors in the rotor and stator parts.

2.1.3 Positive displacement compressor [13]

The compression of air takes place by displacing a mechanical connection that reduces the volume is called positive displacement compressor. (since in thermodynamics, positive displacement of the piston occurs by volume reduction of the piston).

The compressors are further divided by design

Piston - changes in gas volume through the reciprocating piston in the cylinder. As the piston moves down, the gas is sucked in through the suction valve, the gas is compressed as it moves up, and then pushed out of the cylinder by the discharge valve. Pistons can be either driven by crankshaft rotation or directly by another oscillating piston machine (e.g. steam compressor).

- Oil-lubricating, in this case oil is sprayed into the cylinder area under the piston by the crankshaft and the piston ring is wiped back. With this type of compressor, oil vapor enters the compressed air.
- oil-free - it ensures the output of compressed air without oil vapour, so it is suitable for specific purposes (beer tap, aquarium breeding, food industry.

2.2 Piston compressor

In my diploma thesis I deal with piston compressor. Piston compressor is a positive-displacement compressor. The gas is compressed in the working space defined by the cylinder wall, the piston bottom and the cylinder head. The change in this working volume is ensured by the crank mechanism, which is driven by an internal combustion engine or an electric motor. Working of piston compressor takes place in four stages when the piston moves between top dead centre TDC and the bottom dead centre BDC.

2.2.1 Working principle

1. Suction

   The piston moves from TDC to BDC, the work volume increases, resulting in vacuum and opens inlet valve in the cylinder which is used suck the gas at constant pressure.

2. Compression

   The piston moves from BDC and TDC, the working volume is reduced, the intake valve is closed and pressure is increasing.

3. Displacement

   At a certain overpressure discharge valve is opened, the piston continues to TDC, and the gas has been displaced at constant pressure usually into the reservoir.

4. Expansion

   All compressed gas cannot be displaced from the working space, so that the remainder when the piston moves from TDC to BDC must first expand to the low pressure at which the intake valve opens, followed by suction only.

Figure 2. Reciprocating Piston compressor [9]

2.2.2 Main parts [0]

1. Piston

It is a movable part of machines that serves to transfer power between a mechanical device and a liquid or gaseous medium. It moves in the cylinder and is usually attached to the piston rod or directly to the connecting rod. It is sealed on the circumference by piston rings. The piston is the working part of many machines, such as piston pumps, piston engines, hydraulic equipment and many others. If only one side of the piston is working, we are talking about a single-acting piston, if it transmits both sides of the piston, we are talking about a double-acting piston.

2. Connecting rod

It is a specialized machine component for mechanical transmission of drive forces. It is a rod (longitudinal beam), which in the piston machines converts the sliding movement into rotary or vice versa.

One end of the connecting rod is fixed by a pin to the piston (possibly to a crosshead, for example, on steam engines) and the other end to the crankshaft or wheel handle. The connecting rod is one of the most stressed parts of the engine. Therefore, it is usually produced by forging of high-quality alloy steel or solid light alloys for high mechanical strength. It is mainly stressed on buckling, then on tension and bending, because its speed, direction of movement and position change periodically. The eye and the connecting rod bearing are also subjected to flat pressure. Connecting rods must exhibit high operational resistance to shock loads.

3. Crankshaft

It is a technical component of a device that serves to convert rectilinear reciprocating motion to rotational motion or vice versa. It is an essential part of most piston engines and piston pumps. It consists of short, cylindrical pins, fixed to each other by arms. Pins located in the axis of rotation of the shaft are called crankcase. Pins that are offset with respect to this axis are called connecting rods. The offset pins may be implemented in one plane with a flat crankshaft, or in multiple planes on a spatial crank shaft.

4. Crankcase

It is a basic part of the compressor; it includes a crosshead guide and a cylinder flange. Crankcase transmits the forces which occur in the cylinder and the crank mechanism, to the block. Its other features may be lubricating oil reservoir.

5. Cylinder and cylinder head

The cylinder is a mechanical device used for converting compressed air power into mechanical motion. As with hydraulic cylinders, the force across the piston is transferred to the piston rod. When compared to hydraulic cylinders, pneumatic cylinders are generally simpler to use because they use compressed air instead of hydraulic fluid (oil blend with additional additives), which does not contaminate the environment by leaking it.

The cylinder head is a structural part of an internal combustion engine or other piston heat engine that includes inlet and exhaust ducts, valve manifold components in conventional construction machines.

6. Valves

Valves are mechanical devices controlling the flow of air or liquid. They are housed in valve chambers which are located around the circumference of the cylinder or in its head. Plain, self-acting valves are common - they open with vacuum (suction) and over-pressure (discharge), closing with a special plate spring that presses the valve plate onto the seat, closing the flow holes.

Furthermore, piston compressors include,

- performance regulation.
- lubrication of the working area and crank mechanism.
- oil and air separation, respectively gas.
- temperature and pressure measurements.
- over-pressure protection - safety valves.
- cleaning the intake gas respectively air.

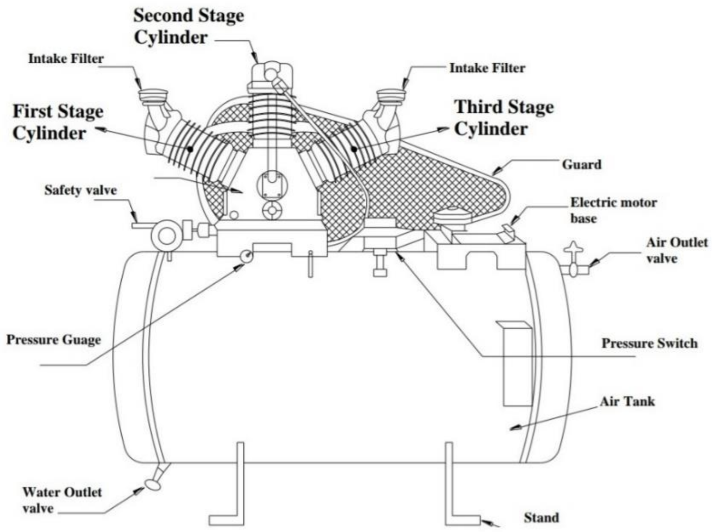

Figure 3 Parts of air compressor [5]

2.2.3 Main Components of Compressed Air Systems

Compressed air systems consist of following major components: Intake air filters, inter-stage coolers, aftercoolers, air-dryers, moisture drain traps, receivers, piping network, filters, regulators and lubricators.

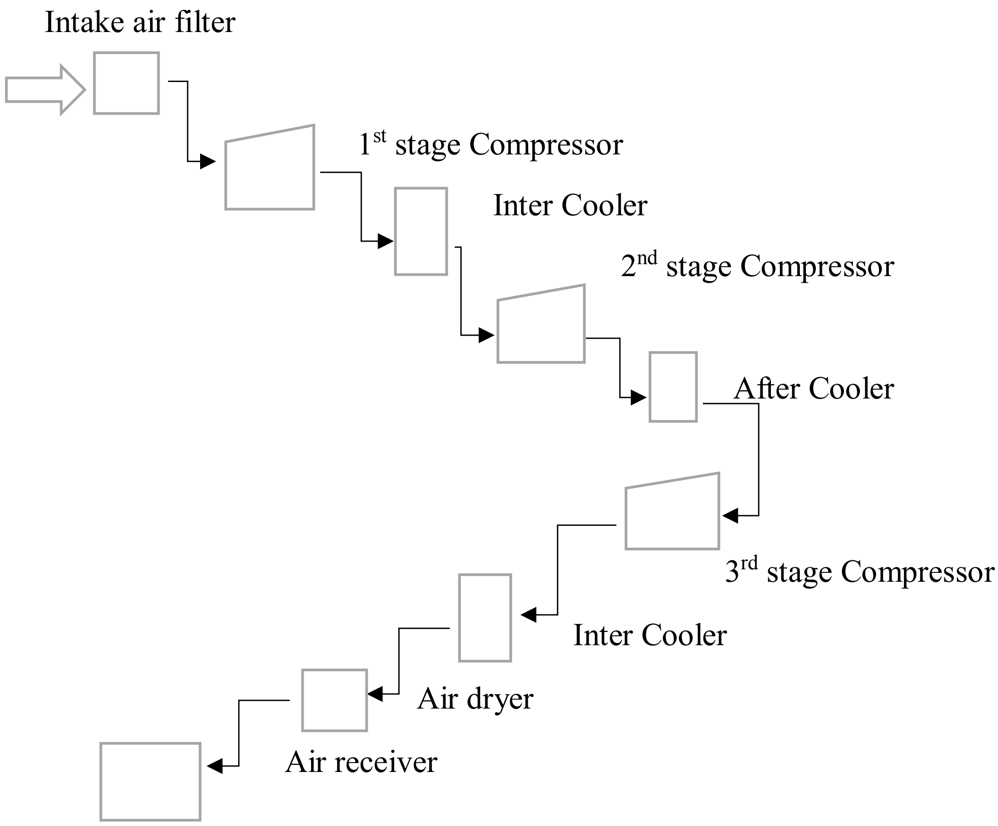

Figure 4 Arrangements of Components of Air Compressor.

3. Compressor Work

The mechanical energy balance is used to measure a compressor's work requirements. Kinetic and potential changes in energy are low on most compressors so flow rate and static head parameters can be neglected. Like pumps, by using an efficiency, friction can be grouped into the work term. The fluid cannot be treated as incompressible unlike pumps, therefore a differential equation is needed.

$$pV = \frac{p}{\rho} = \text{constant} \tag{3.1}$$

$$W = \frac{p_1}{\rho_1} \ln \frac{p_2}{P_1} \text{ or}$$

$$W = P_1 V_1 \ln \frac{p_2}{p_1} \tag{3.2}$$

3.1 Working principle

The piston moves downward and draws air into the cylinder in a piston compressor with a valve mechanism and two valve disks. The largest disc bends downwards, allowing the air to pass through. The large disc bends again when the piston moves upwards to seal against the valve seat. Then the compressed air is forced into the valve seat through the hole and delivered to the end of the process.

3.2 p-V Diagram for reciprocating compressor

To understand the concepts of reciprocating compressors, a description of a few fundamental thermodynamic principles is required. Compression takes place as a four-part cycle within the cylinder which occurs with each piston movement (two strokes per cycle). Compression, discharge, expansion and intake are the four parts of the cycle.

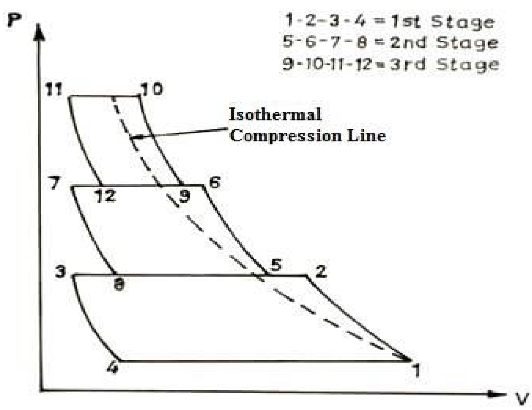

Figure 5 p-V Diagram for reciprocating compressor. [11]

3.3 Isothermal Compression [11]

The isothermal change takes place at a constant temperature. Gas only changes its volume and pressure. In fact, this action assumes a perfect heat exchange of the gas with the cooling water, so that the constant thermodynamic temperature condition can be maintained. It represents a saving of labour we have to spend on compressing gas. However, the actual events are rather adiabatic.

$$p_1 V_1 T_1 = p_2 V_2 T_2$$

$$T_1, T_2 = \text{constant}, \Delta T = 0$$

$$p_1 V_1 = p_2 V_2 \qquad (3.3)$$

Isothermal compression is an important because we are dealing it in real compressors. The lower the temperature, the higher the isothermal approaches the "p" and "V" axes.

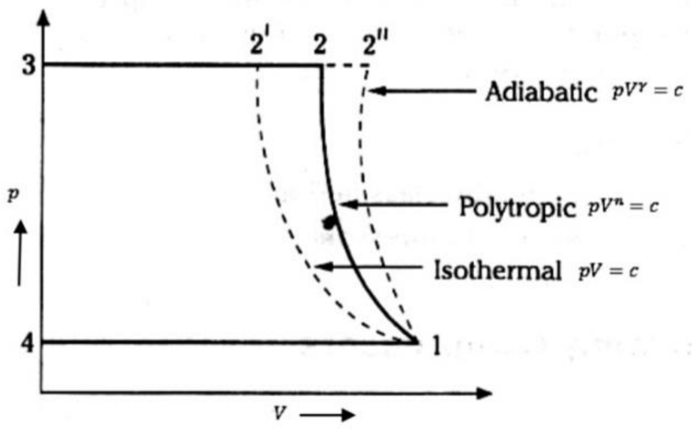

Figure 6 p-V diagram [5]

3.4 Isentropic Compression

In isentropic compression, external forces act, so the internal energy of the gas increases and its increases the temperature. During this compression, the gas does not exchange heat with the cooling water. Entropy of gas does not change. We can see the changes that take place very quickly. In practice, this is the majority of compressions and expansions in thermal machines. Isentropic change is described by the equation:

$$pV^{\gamma} = \frac{P}{\rho^{\gamma}} = \frac{P}{\rho^{c_p/c_v}} = constant \qquad (3.4)$$

The equation can be rearranged to solve density in terms of one known pressure and substituted into the work equation, which then can be integrated.

$$\frac{p}{\rho^{\gamma}} = \frac{p_1}{{\rho_1}^{\gamma}}$$

$$\rho = [\frac{p}{p_1}]^{1/\gamma} \rho_1$$

$$W = \int_{p_1}^{p_2} \frac{dp}{[\frac{p}{p_1}]^{1/\gamma} \rho_1} = \frac{{p_1}^{1/\gamma}}{\rho_1} \int_{p_1}^{p_2} \frac{dp}{p^{1/\gamma}}$$

$$W = \frac{p_1 \gamma}{(\gamma - 1)\rho_1} [(\frac{p_2}{p_1})^{1-\frac{1}{\gamma}} - 1]$$

$$W = \frac{p_1 \gamma}{\rho_1(\gamma - 1)} [(\frac{p_2}{p_1})^{\frac{\gamma-1}{\gamma}} - 1]$$

$$W = \mathrm{p_1 V_1} \frac{\gamma}{(\gamma-1)} [(\frac{p_2}{p_1})^{\frac{\gamma-1}{\gamma}} - 1] \text{ or}$$

$$W = \mathrm{p_1 V_1} \frac{n}{(n-1)} [(\frac{p_2}{p_1})^{\frac{n-1}{n}} - 1] \qquad (3.5)$$

The ratio of the actual work to the isentropic work is called isentropic efficiency. The outlet temperature may be calculated from

$$T_2 = T_1 [\frac{p_2}{p_1}]^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = T_1 [\frac{p_2}{p_1}]^{\frac{n-1}{n}} \qquad (3.6)$$

Where γ = Adiabatic process

n = Polytropic process

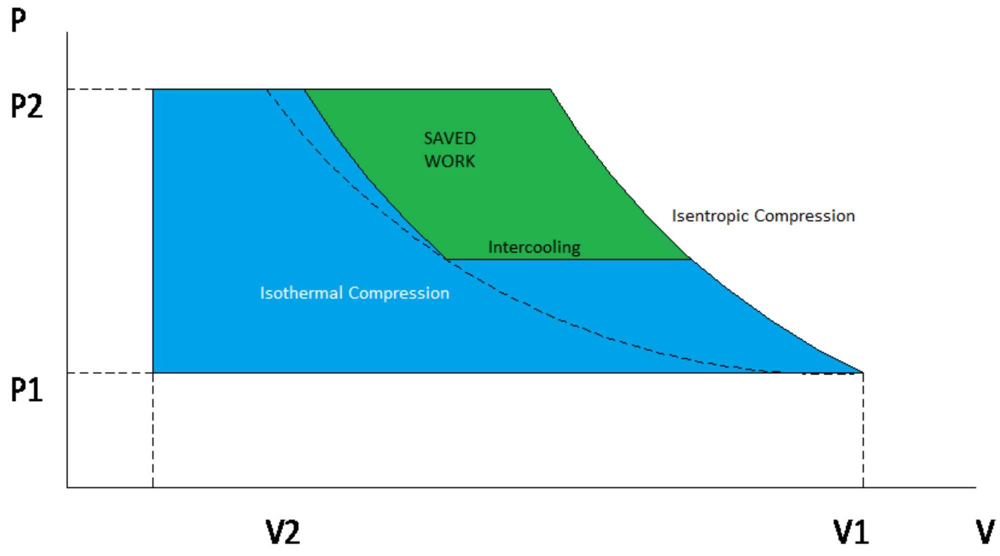

Figure 7 p-V diagram for isentropic compression. [12]

4. Compressor cooling

The need for cooling becomes an essential part of the manufacturing process. The vast majority of technical equipment is currently associated with the release of large amounts of heat. Often one is the undesirable heat that can negatively affect the device itself. This heat must be removed and neutralized with a suitable coolant.

An improperly selected or unreliable method may cause damage to the refrigerated equipment. The use of cool water to cool machines leads to improved performance and longer life. Water is the most commonly used substance to remove or transfer thermal energy from a body whether in solid, liquid or gaseous form. Water is the most commonly used medium because it is not toxic, is readily available and has a high heat capacity (i.e. the ability to retain energy in the form of heat). Air that is heated to high temperatures by compression is to be cooled to an approximate ambient temperature. Too high temperature can cause the compressor to malfunction; it can also ignite the oil vapor that enters the compressed air during oil spray. Compressors are designed as multistage, resulting in low cylinder loading and low gas temperature rise during cylinder compression.

The cooling device can consist of intercoolers, which are assigned to the individual stages of the compressor, the coolant circuit and, if necessary, to the following. a pump that drives water in a closed circuit.

The aim is to cool down machine parts and reduce the volume and temperature of the heated gas after compression in each stage. At the same time, with the cooling of the air during several stages of compression, we try to approach isothermal compression and consequently increase the efficiency of the compressor. Cooling enables reliable operation of the compressor, improves the lubrication of the cylinder walls, increases "η" (transport efficiency). Suction gas does not heat the cylinder wall. We can cool with air or water.

- Air – In small and mobile compressors, heads and cylinders are provided with ribs - thereby increasing the heat dissipation area; the radiator consists of a ribbed tube.
- Water – In large and medium compressors, stable compressors; the water flows in the cavities between the cylinder and the casing or in the compressor head cavities.

Several methods are used to cool the working gas during compression, including combinations they are,

Surface Cooling or Indoor Cooling

It consists in feeding coolant to the shell of each stage. For this purpose, the compressor is double-walled and cooling fluid flows between the casing. The compressed gas is cooled continuously and the result is a decrease in the specific internal work and the compressor exit gas temperature. Surface cooling is less efficient and so is used in compressors with low compression in one stage.

Intercooling or external cooling compressors

For more efficient cooling is preferable for the selected compressor stage, the gas compressed in compressor pay out the recuperative heat exchanger where the coolant gas by means of cooling. It is a much more efficient type of cooling than in the case of surface cooling. The minimum cooling temperature is determined by the coolant temperature. The cooling gas temperature of the working gas should be equal to the intake gas working temperature for the most efficient cooling. This cannot always be achieved, especially if the suction temperature is equal to the ambient temperature. External cooling can be done in steps, so the least necessary compression work can be achieved, which is structurally feasible.

Intercoolers are most often designed as tubular heat exchangers (finned tubes), where coolant (mostly water) flows in the tubes.

4.1 Inter-coolers of piston compressor [4]

Between successive stages of a multi-stage compressor, inter-coolers are provided to remove compression heat, thus reducing compression work (power requirements). By reducing the specific volume by cooling the air, compression work (power requirements) is reduced. Intercooling thus alters the machine's overall efficiency. Ideally, at each stage of a multi-stage machine, the temperature of the inlet air should be the same as at the first stage. This is called Isothermal compression or "perfect cooling". In practice, however, the inlet air temperatures at subsequent stages are higher than normal levels, leading to higher power consumption, as higher.

Due to its high heat transfer rate, air-to-liquid intercoolers are generally used compared to air-to-air intercoolers. Usually, water is used as an intermediate fluid in air-to-liquid intercooler. Due to additional parts like (water circulation pump, fluid and plumbing) that make up the system, air-to-liquid intercoolers are usually heavier than their air-to-air counterparts.

Function of intercooler

- Atmospheric air contains moisture, and in addition, as it passes through some compressors, the air may collect oil vapour. Cooling down or below the initial temperature of the air will remove the moisture below to the dew point, improving the air quality.
- Another purpose of the intercooler is to improve compression efficiency. This is achieved by reducing compression work (power requirements).
- The air that comes out of the compressor have high pressure and temperature.
  High temperature of the air can cause problems for pneumatic tools, so compressed air of outlet temperature is reduced by using intercoolers.
- To achieve equivalent output for every 4°C rise in inlet air temperature results in energy consumption of 1 percent.

4.1.1 Shell and tube type intercooler

A heat exchanger like an intercooler is a mechanical device that is used at different temperatures for heat exchange between two fluids. There are different types of intercoolers available, but the Shell and Tube type is most widely used. It is most commonly used in different fields such as power plants, nuclear and chemical industries, oil refineries.

This high level of acceptance is due to the relatively large ratio of heat transfer area to volume and weight, easy methods of cleaning, simple components to replace etc. The intercooler shell and tube type consist of several tubes through which one fluid flows. Another fluid flows through the shell containing the tubes and other supporting object. The exchange of heat between the two fluids takes place through the tube walls.

4.1.2 Classification of Shell and Tube heat exchanger

Fixed Tube Sheet- A fixed-tube heat exchanger has straight tubes that are protected by tube sheets welded to the shell at both ends. The structure may have bonnet-type channel covers, removable channel covers or integral tube sheets.

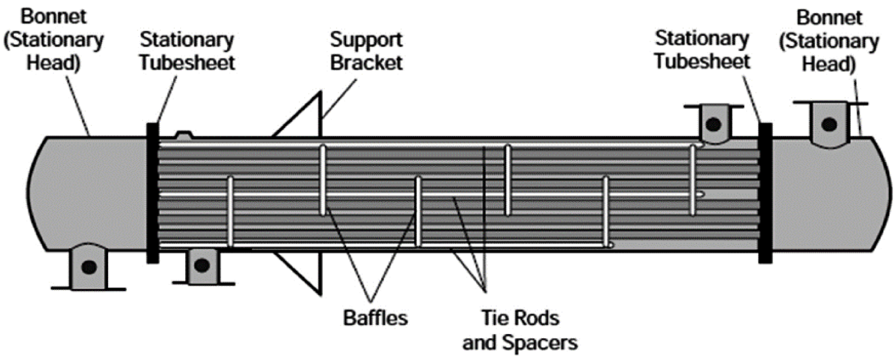

Figure 8 Fixed Tube Heat Exchanger [4]

Floating head- The most versatile type of Sheet is the floating-head heat exchanger, and also the most expensive. One tube sheet is fixed relative to the shell in this design, and the other within the shell is free to "float." This allows for free expansion of the tube bundle and cleaning of the tubes both at inside and outside.

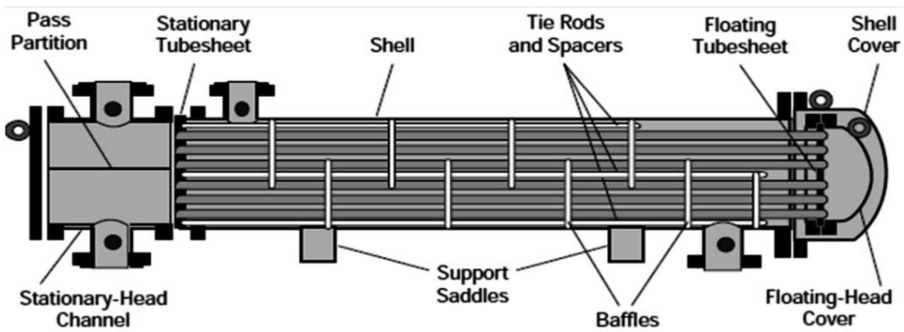

Figure 9 Pull through Floating head exchanger [4]

4.1.3 Based on service

It may be single phase (such as heating or cooling of gas or liquid) or two-phase (such as condensation or vaporization). Because a sheet has two sides, this can lead to several service combinations.

Usually, services can be classified as follows

- Single-phase (both tube side and shell side).
- Condensing (one side single-phase and the other side condensing).
- Vaporizing (one side single-phase and the other side vaporizing).
- Condensing/vaporizing (one side vaporizing and the other side condensing).

4.2 External cooler

Aftercoolers are heat exchangers for air compressor to cool the discharge air. They use either air or water to remove moisture from compressed air. Aftercoolers reduce certain amount of water vapour by condensing water vapor into liquid form in a compressed air system. Aftercoolers are an excellent way to reduce moisture in a compressed air system in combination with a separator. Liquid water causes significant damage to equipment in a distribution or process production system.

To ensure proper functionality of pneumatic or air handling devices which are part of production processes, an aftercooler is required. Aftercoolers can use mechanisms that are either air-cooled or water-cooled.

Functions of compressed air aftercoolers

- Cool air discharged through the heat exchanger from air compressors.
- Reduce fire risk (Hot compressed air pipes may be an ignition source).
- Reduce the level of compressed air moisture content.
- Protect downstream equipment from overheating.
- It Increase the capacity of the system.

4.2.1 Types of aftercoolers

There are two basic types of air aftercoolers,

- air-cooled
- water-cooled

4.2.1.1 Air cooled aftercoolers

To cool the hot compressed air, air-cooled aftercoolers use ambient air. The compressed air flows into the air-cooled aftercooler. The compressed air travels through the aftercooler either finned tubes or corrugated aluminium sheets while the motor driven fan force the ambient air over the cooler the cooler or ambient air removes heat from compressed air.

4.2.1.2 Belt Guard Air Cooled Aftercooler

This type of aftercooler mounts on the compressor v-belt guard. The belt pulley of the compressor has fins designed to force ambient air over the air-cooled aftercooler and compressor. The air that passes over the aftercooler facilitates heat transfer. The air also passes with the help of pulley over the compressor to maintain the operating temperature.

4.2.1.3 Water-Cooled Pipe Line Aftercooler

A water-cooled aftercooler pipe line comes in various models. A shell and tube heat exchanger/aftercooler are the most common style of compressed air service. The aftercooler pipe line consists of a shell fitted inside with a bundle of tubes. The compressed air typically flows in one direction through the tubes as water flows in the opposite direction on the shell side. Heat is transferred to the water from the compressed air. As the compressed air cools, water vapor forms. The moisture separator and drain valve removes the moisture. To maintain a steady temperature and reduce water usage, a modulating valve is requested. It is possible to fix or remove the tube bundles.

The disadvantages of this type are high water use and complicated heat recovery. The benefits of using a water-cooled aftercooler involve increased heat transfer and no electrical energy required.

5. Flow measurements in piston compressor. [16]

The Pressure, temperature and the water flow in the piston compressor is measured using sensors Pressure is measured with help of transmitter pressure sensor. Temperature is measured using thermocouple type “K” and the water flow in the compressor is measured by paddle wheel flow meter.

The measurement of the flow rate and the amount of fluid flowing very important in measurements. There are often many problems with the design of the sensor its selection and installation in terms of type (liquid, steam, gas) and properties (e.g. pressure, temperature, density, viscosity, solids contamination, electrical conductivity).

Also important are the type of flow (laminar or turbulent), the shape of the velocity profile in the pipe (channel), the time change of the measured flow. All these factors influence the choice of the physical principle of the sensor for a given application. There are also many ways to measure flow. Among the most commonly used are cross-sectional flowmeters. When using these flowmeters, the differential pressure is measured, which is then converted to volume or mass flow rate. As a result, we need to know more data than just the difference in pressure for accurate flow measurement. Most often, you need to know the temperature of the medium, exact density and accurate flow rate.

Basic types of flowmeters

- cross-flow flowmeters (primary throttling elements)
- velocity flowmeters
- Variable cross-section flowmeters
- turbine and vane flowmeters
- volumetric flowmeters
- deformation flowmeters
- ultrasonic flowmeters
- inductive flowmeters,
- flow meters with fluid marking

5.1 Pressure measurement [7]

The pressure flow in the compressor is calculated using transmitter pressure sensor. Pressure sensors are used in hundreds of everyday applications for control and monitoring. Other variables such as fluid/gas flow and speed can also be measured indirectly using pressure sensors. Alternatively, pressure transducers, pressure transmitters, pressure indicators, piezometers and manometers can be called as pressure sensors.

Transmitter pressure sensor

It is one of the pressure transducer subgroups, involving additional features for resetting and calibration. For example, with some sensor types, the measurement span can be reset over large ranges. Terms such as "scale down," "span reset" or "turn down" usually refer to this calibration option. For example, a transmitter with a range of 0 to 400 psi and a range reset of 1/10 can be measured to a range of 0-40 psi while still delivering a full output signal (4-20 mA).

The zero points can also be shifted over a wide range and the damping of the output signal can be optimised between 0 and 32 seconds. It is also possible to measure, test and reset smart transmitters such as which also have logging capabilities either through the control desk or hand terminals.

Figure 10 Pressure transmitters [10]

5.2 Temperature measurement

The temperature in the compressor is measured using thermocouple type k. A temperature sensor is a device that provides temperature measurement through an electrical signal, typically a thermocouple. A thermocouple is made of two dissimilar metals that produce an electrical voltage proportional to temperature changes. Contact sensors include thermistors and thermocouples that touch the object to be measured, and non-contact sensors measures the heat radiation released by a heat source to determine the temperature. The latter group measures temperature from a particular distance and is often used in harmful environments.

Thermocouple [17]

A thermocouple is a type of sensor used to measure temperature that is produced by joining two different metals at one end. The hot junction is at the joined end and cold junction is at the other end of the dissimilar metals. At the last point of thermocouple material, the cold junction is formed. A small voltage is created if there is a temperature difference between the hot junction and the cold junction. This voltage is referred to as an EMF (electromotive force) and can be used to measure and indicate temperature**.**

Thermocouple type K

The thermocouple Type K has a positive leg for chromium and a negative leg for aluminium (Nickel-5 %, aluminium and silicon). For use in oxidizing and completely inert conditions, Type K thermocouple is suggested. Because their resistance to oxidation is better and they are most widely used at temperatures above 1000°F. Type K thermocouple should not be used in sulphur environments or in vacuum conditions.

5.3 Measurement of water flow

The flow of water is measured using Paddle wheel flow meter. In order to calculate flow indirectly, flow measurement methods other than positive displacement flow meters rely on forces produced by the flowing stream as it overcomes a known constriction. By measuring the velocity of fluid over a known area, flow can be measured. Tracer methods can be used to deduce the flow rate from the change in a dye or radioisotope concentration for very large flows.

Paddle wheel flow meter [8]

Paddle wheel flow meters are composed of three main components: paddle wheel sensor, pipe fit and display/controller. The paddle wheel sensor is a freely rotating wheel/impeller with embedded magnets perpendicular to the flow and rotates when inserted into the flowing medium. The paddle wheel meter generates a frequency and voltage signal proportional to the flow rate as the magnets in the blades spin past the sensor. When the flow increases the voltage input and the frequency increases.

Figure 11 Paddle wheel flow meter [6]

The paddle wheel meter is designed to be either' in-line' or insertion style into a pipe fitting. These are available with a wide range of appropriate styles, methods of connection, and materials such as polypropylene, and stainless steel. The paddle wheel meter requires a minimum run of straight pipe before and after the sensor, similar to turbine meters. For receiving the signal from the paddle wheel meter flow displays and controllers are used and convert it into actual flow rate or total flow values.

6. Design of piston cooler [13]

Piston compressor 1 TSK 115

The designation of piston compressors is used both by letters and numbers, which express the machine's technical data. Designation 1 TSK 115 Mark.

- No. 1 - indicates the number of cylinders, i.e. one-cylinder compressor
- Letter T - expresses the number of stage - three stages,
- letter S - stands for machine - standing
- letter K - indicates machine type - compressor
- digit 115 - denotes the diameter of the cylinder of the first stage of the compressor in mm.

Figure 12 Piston compressor 1TSK 115

It is an oil-lubricated piston compressor equipped with an oil tank to lubricate the equipment. This ensures smooth operation of the compressor, reduces friction and wear on the parts (piston, bearings, seals, etc.). On the other hand, if the oil is excess, there is more force on the piston returning from the top dead centre to the bottom dead centre, the cylinder walls are not well lubricated, and the rings are sintered over time. The oil is sprayed into the cylinder chamber under the crankshaft piston. The piston ring is wiped back. Oil vapours and aerosols get into the compressed air. This often results in the ignition of oil vapours. This can be avoided by selecting a suitable filter to capture the oil vapor, with activated carbon. The efficiency and lifetime of activated carbon is influenced by the temperature of the compressed air and its humidity. Another measure is the choice of oil with low evaporation and high oxidation stability.

The mechanically stressed components of the compressor are made of high-quality materials to reduce wear. They usually also work at lower speeds. All three stages of the compressor are placed one above the other in one common cylinder. They are protected by safety valves.

Three-stage compressors use graduated pistons. All three compression stages are in one cylinder (differential piston grading is provided by differential piston). The compressor is driven by an electric motor using a V-belt. The V-belt transmits the torque between the shafts. Since the V-belt transmits torque at relatively low tension, the V-belt drive achieves some advantages, such as greater efficiency against flat belt drive, or greater drive safety, even with low pulley circumscription. At the same time, it allows slipping of the belt in case of high impact load.

The current method of cooling the compressor is cooled with water. The radiator is of simple design in which compressed air resp. gas gives off heat to cooling water. It is a spiral tube through which compressed air flows. The coolers are placed in a container filled with cooling fluid - water. The compressor cylinder is provided with a casing that is cast in one piece. The water we used to cool the air between the stages can be introduced into the cylinder shell. This saves water consumption.

6.1 Design Layout of piston compressor with coolers.

It is a simple wire diagram in which all three stage of compressor and both Intercoolers and Aftercooler is listed. Also, the amount of pressure, temperature and mass flow of both compressor and coolers is marked at the respective stage.

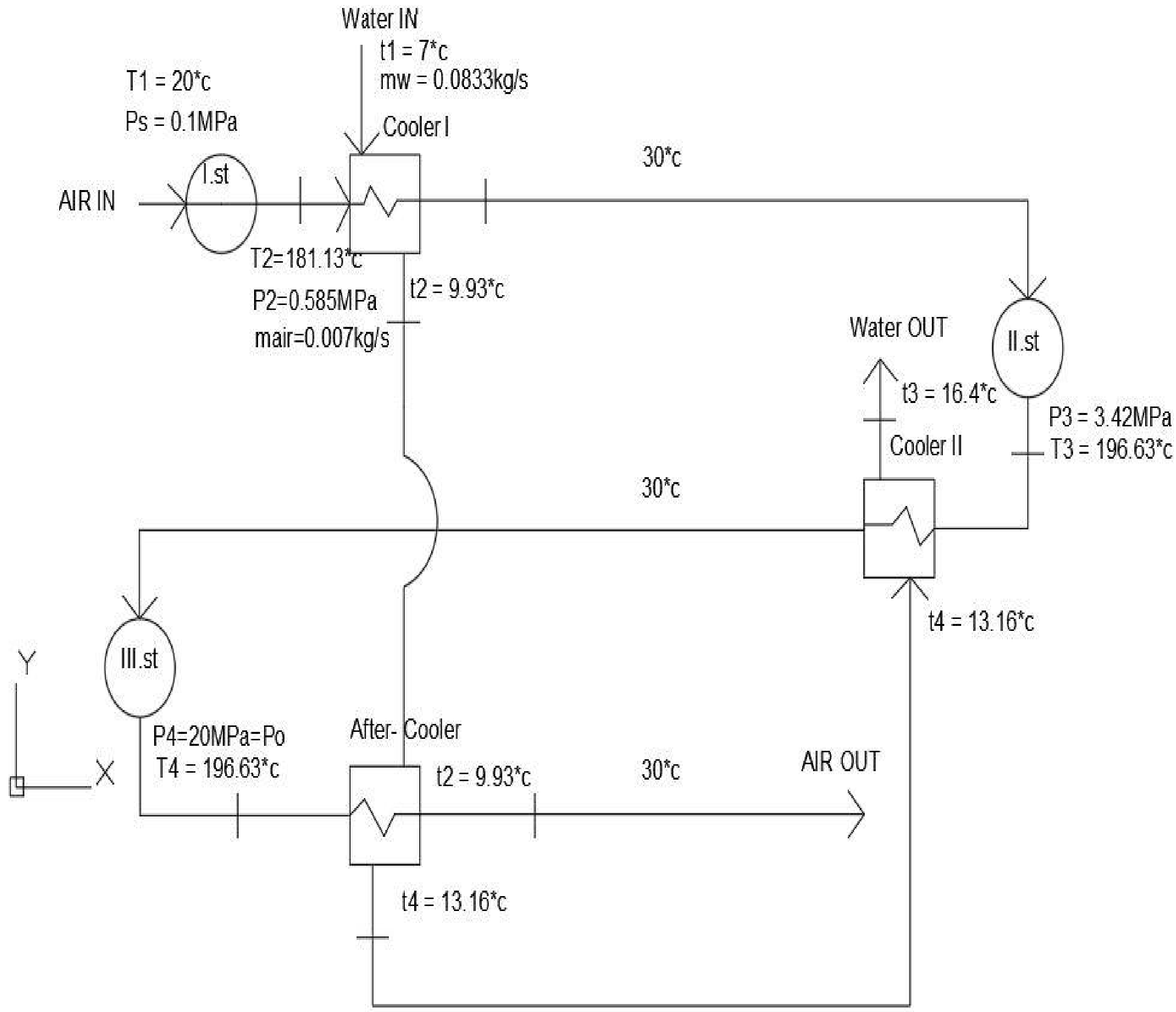

Figure 13 Wire diagram of compressor and coolers

6.2. Schematic design of cooler

This is the new design model shell and tube heat exchanger which I designed in solid works V5 software. The air flows through inside the spiral tube. Water flows between spiral tube and the shell, heat exchange takes place between air and water which is used to cool the discharge air from the compressor in all three stage.

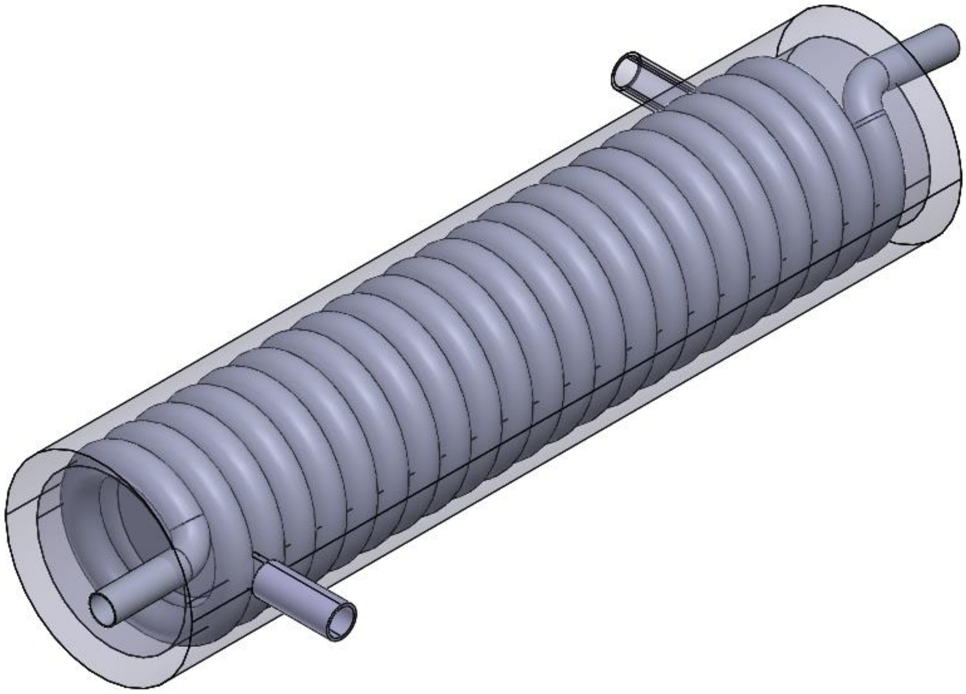

Figure 14 3-D design model of cooler

7. Calculation

The cooling of multi-stage piston compressor for 1TSK 115 Piston compressor with following parameters.

Suction air pressure p_s = 0.1MPa

Discharge air pressure p_o = 20 MPa

Suction air temperature T_1 = 20 °C = 293K

Discharge air temperature T' = 30 °C = 303K

Air density (at suction) ρ = 1.189 Kg/m^3

Compressor performance m_{air} = 20m^3/h = (20* 1.19) / 3600 = 0.007 kg/s

Electrometer output P_{el} = 5 kW

Rotations r = 800 rpm

Polytropic exponent n = 1.33

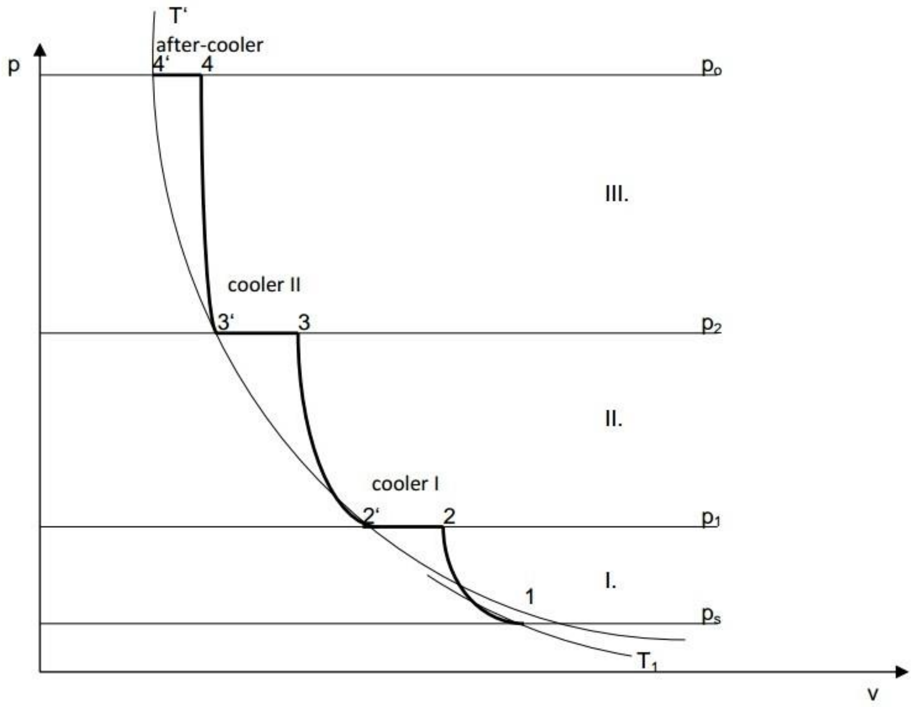

Figure 15 pV diagram for three stage piston compressor with coolers

Compression ratio $\varepsilon_c = \sqrt[3]{\frac{p_o}{p_s}}$ (7.1)

$= \sqrt[3]{\frac{20}{0.1}}$

$\varepsilon_c = 5.848$

1. Pressure after 1st stage of compressor

p $= \varepsilon_c * p_s$ (7.2)

$= 5.848 * 0.1$

$p_2 = 0.585\text{MPa}$

2. Pressure after 2nd stage of compressor

$p_3 = \varepsilon_c * p_1$ (7.3)

$= 5.848 * 0.584$

$p_3 = 3.42\text{MPa}$

3. Pressure after 3rd stage of compressor

$$p_4 = \varepsilon_c * p_2 \tag{7.4}$$

$$= 5.848 * 3.42$$

$$p_4 = 20 \text{ MPa} = p_o$$

Calculation for outlet temperature of compressor

1. Temperature after 1st stage of compressor

$$T_2 = T_1 * \varepsilon_c^{\frac{n-1}{n}} \tag{7.5}$$

$$= 293 * 5.848^{\frac{1.33-1}{1.33}}$$

$$= 293 * 1.55$$

$$T_2 = 454.13 \text{ K}$$

$$T_2 = 181.13 \text{ °C}$$

2. Temperature after 2nd and 3rd stage of compressor

$$T_3 = T_4 = T^{|} * \varepsilon_c^{\frac{n-1}{n}} \tag{7.6}$$

$$= 303 * 5.848^{\frac{1.33-1}{1.33}}$$

$$T_3 = T_4 = 469.63 \text{ K}$$

$$T_3 = T_4 = 196.63 \text{ °C}$$

For discharge air temperature 30 °C

$$C_P = 1023 \text{ J/kg*K}$$

Determination of specific heat dissipated by cooling Q:

1. Power of the 1st stage of compressor

Q_1 = m * c_p air * ΔT

= m * c_p air * (T_2 – $T^{|}$) (7.7)

= 0.007 * 1023 * (181.13 – 30)

Q_1 = 1021.2 W

2. Power of the 2nd stage of compressor

Q_2 = m * c_p air * ΔT

= m * c_p air * (T_3 – $T^{|}$) (7.8)

= 0.007 * 1023 * (196.63 – 30)

Q_2 = 1126 W

3. Power of the 3rd stage of compressor

Q_3 = m * c_p air * (T_4 – $T^{|}$) (7.9)

= 0.007 * 1023 * (196.63 – 30)

Q_3 = 1126 W

Calculation for outlet temperature of coolers

For water:

Inlet temperature t_1 = 7 °C

Specific heat C_{pw} = 4180 J/kg*K

Mass flow m_w = 300 l/h = 0.3 m^3/h.

m_w= 0.0833 kg/s

1. Outlet temperature of 1st cooler

$$t_2 = \frac{Q_1}{m_w * C_{pw}} + t_1 \tag{7.10}$$

$$= \frac{1021.2}{0.0833*4180} + 7$$

t_2 = 9.93 °C

2. Outlet temperature of After cooler

$$t_4 = \frac{Q_3}{m_w * C_{pw}} + t_2 \tag{7.11}$$

$$= \frac{1126}{0.0833*4180} + 10.11$$

t_4 = 13.16 °C

3. Outlet temperature of 2nd cooler

$$t_3 = \frac{Q_2}{m_w * C_{pw}} + t_4 \tag{7.12}$$

$$= \frac{1126}{0.0833*4180} + 13.54$$

t_3 = 16.40 °C

Calculation of Mean temperature difference of coolers

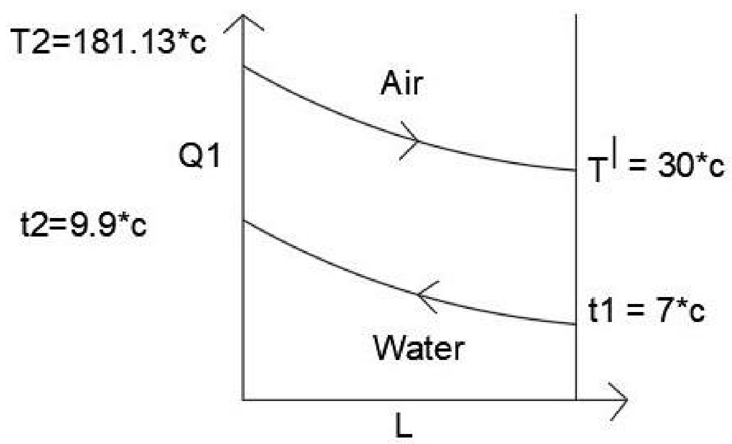

Figure 16 Temperature flow of 1st cooler

1. Mean temperature difference of 1st cooler

$$MTD_1 = \frac{[(T_2 - t_2) - (T^{|} - t_1)]}{\ln{(T_2 - t_2)/(T^{|} - t_1)]}} \tag{7.13}$$

$$= \frac{[(181.13 - 9.93) - (30 - 7)]}{\ln{[(181.13 - 9.93)/(30 - 7)]}}$$

MTD_1 = 73.8 °C

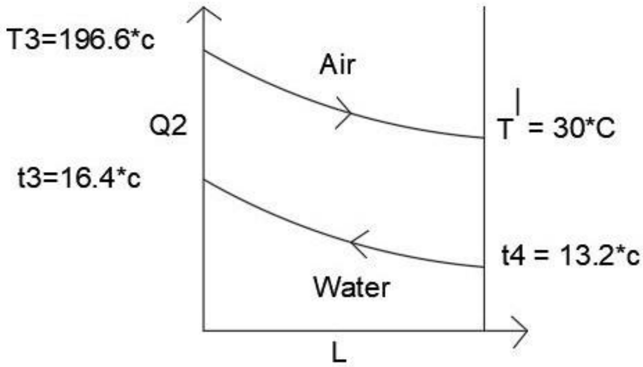

Figure 17 Temperature flow of 2nd cooler

2. Mean temperature difference of 2nd cooler

$$MTD_2 = \frac{[(T_3 - t_3) - (T^{|} - t_4)]}{\ln{(T_3 - t_3)/(T^{|} - t_4)]}} \tag{7.14}$$

$$= \frac{[(196.63 - 16.4) - (30 - 13.16)]}{\ln{[(196.63 - 16.4)/(30 - 13.16)]}}$$

MTD_2 = 68.9 °C

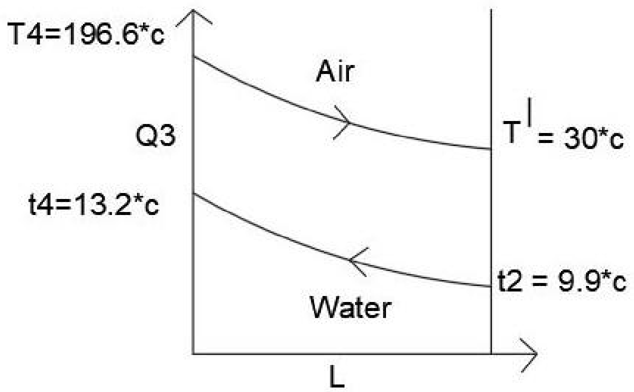

Figure 18 Temperature flow of 3rd cooler

3. Mean temperature difference of After cooler

$$MTD_3 = \frac{[(T_4 - t_4) - (T^{|} - t_2)]}{\ln\,[(T_4 - t_4)\,/\,(T^{|} - t_2)]} \quad (7.15)$$

$$= \frac{[(196.63 - 13.16) - (30 - 9.93)]}{\ln\,[(196.63 - 13.16)\,/\,(30 - 9.93)]}$$

$$MTD_3 = 73.8\ °C$$

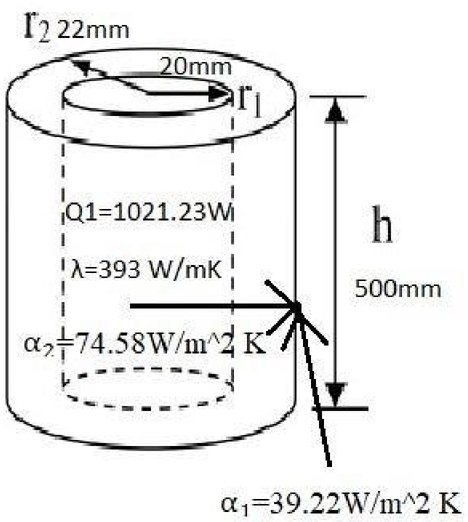

Figure 19 Heat transfer coefficient in copper tube of cooler I

Calculation of air flow section for 1st cooler

Cooling power capacity	Q_1 = 1021.23 W
Specific heat capacity	C_{pair} = 1023 J/kg*K
Inlet temperature of compressor	T_2 = 181.13 °C
Discharge air temperature of compressor	$T^{|}$ = 30 °C
Average temperature	$T_m = \frac{T_2 + T^{|}}{2}$
	T_m = 105.6 °C
Pressure of the compressor	p_2 = 0.585MPa

Thermal conductivity of air λ_{air} = 0.0307 W/m*K

Density of air ρ_{air} = 6.332 kg/m^3

Kinematic viscosity of air $\eta_{air} = 3.54 * 10^{-6}$

Dynamic viscosity of air $\mu_{air} = \rho_{air} * \eta_{air}$ (7.16)

$= 6.332 * 3.54 * 10^{-6}$

$\mu_{air} = 2.24 * 10^{-5}$ Pa*s

mass of the air flow m_{air} = 0.007 kg/s

Outer diameter of copper tube D = 22 mm

Inner diameter of copper tube d = 20 mm

Thermal conductivity of copper λ_{cu} = 393 W/m*K

Cross section of copper tube $A_{cu} = \frac{\{(d/1000)\ \hat{}2\} * 3.14}{4}$ (7.17)

$= \frac{\{(20/1000)\ \hat{}2\} * 3.14}{4}$

$A_{cu} = 0.000314\ m^2$

Volume of the air flow $V_{air} = \frac{m_{air}}{\rho_{air}}$ (7.18)

$= \frac{0.007}{6.332}$

$V_{air} = 0.001043\ m^3/\ s$

Velocity of air $v_{air} = \frac{V_{air}}{A_{cu}}$ (7.19)

$= \frac{0.001043}{0.000314}$

v_{air} = 3.322 m/s

Prandtl number $Pr = (\frac{\rho_{air} * \eta_{air} * C_{pair}}{\lambda_{air}})\hat{}0.43$ (7.20)

$= (\frac{6.332*3.54*10^{-6}*1023}{0.0307})\hat{}0.43$

$= 0.7470^{0.43}$

$Pr = 0.8820$

Reynolds number $Re = (\frac{(v_{air}*d)/1000}{\eta_{air}})\hat{}0.8$ (7.21)

$= (\frac{3.322*20)/1000}{3.54*10^{-6}}\}\hat{}0.8$

$= (1.88*10^4)\hat{}0.8$

$Re = 2622.82$

Nusselt number $Nu = 0.021*Pr*Re$ (7.22)

$= 0.021*0.8820*2622.82$

$Nu = 48.6$

Heat transfer coefficient $\alpha_2 = \frac{Nu * \lambda_{air}}{d/1000}$ (7.23)

$= \frac{48.6 * 0.0307}{20/1000}$

$\alpha_2 = 74.58$ W/ m^2*K

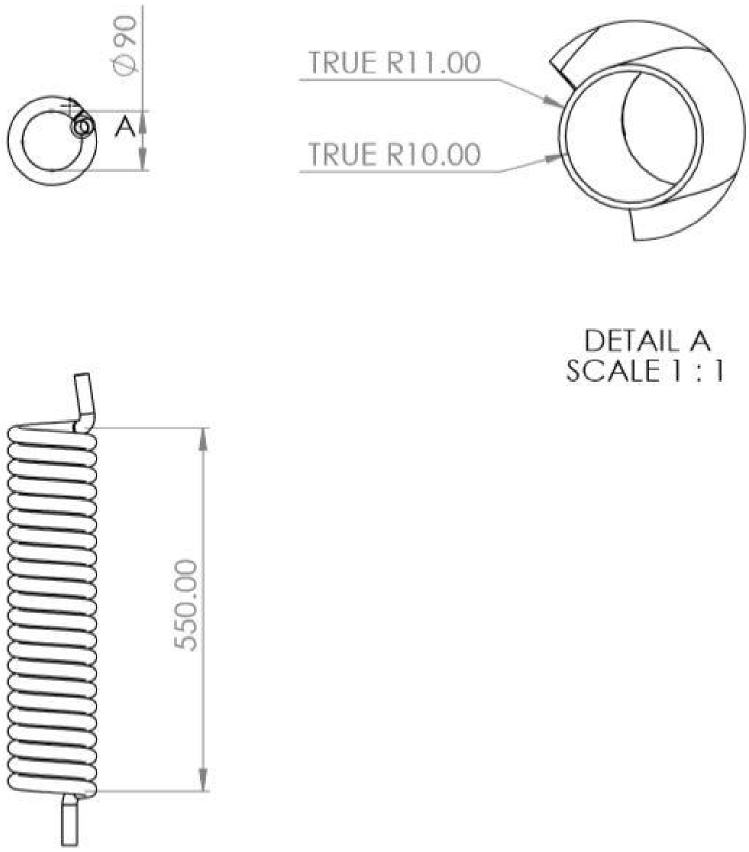

Figure 20 Schematic view of air flow tube in Cooler I

Calculation of Water flow section for 1st cooler

Cooling power capacity Q_1 = 1021.23 W

Specific heat capacity C_{pw} = 4180 J/kg*K

Inlet temperature of cooler t_1 = 7 °C

Discharge temperature of cooler t_2 = 9.9 °C

Average temperature $T_m = \frac{t_1 + t_2}{2}$

T_m = 8.5 °C

Thermal conductivity of water λ_w = 0.0058 W/m*K

Density of water ρ_w = 999 kg/m^3

Kinematic viscosity of water $\eta_w = 1.31 * 10^{-6}$

Dynamic viscosity of water $\mu_w = \rho_w * \eta_w$ (7.24)

$= 999 * 1.31 * 10^{-6}$

$\mu_w = 1.30 * 10^{-3}$ Pa*s

mass of the water flow $m_w = 0.0833$ kg/s

Outer diameter of Iron tube $D_1 = 150$ mm

Inner diameter of Iron tube $D_2 = 90$ mm

Thickness of space $t = \frac{(D_1 - D_2 - 2*D)}{4}$ (7.25)

$= \frac{(150-90-2*22)}{4}$

$t = 4$mm

surface area of tubes $A_1 = \frac{(3.142 *(D_2+2*t+ D) *D}{10^6}$ (7.26)

$= \frac{(3.142 *(90+2*4+22) *22}{10^6}$

$A_1 = 0.00829\ m^2$

Cross section of outer diameter of Iron tube $SD_1 = \frac{\{(D_1/1000)\ ^2\} *3.14}{4}$ (7.27)

$= \frac{\{(150/1000)\ ^2\} *3.14}{4}$

$SD_1 = 0.018\ m^2$

Cross section of inner diameter of iron tube $SD_2 = \frac{\{(D_2/1000)\ ^2\} *3.14}{4}$ (7.28)

$= \frac{\{(90/1000)\ ^2\} *3.14}{4}$

$SD_2 = 0.006\ m^2$

Surface area of ring $S_{ring} = SD_1$ - SD_2 (7.29)

S_{ring} = 0.011 mm

Length of the ring L_{ring} = 3.14 *(D_1-2*t-D) (7.30)

= 3.14 *(150-2*4-22)

L_{ring} = 377mm

Cross section of Iron tube A_{fe} = S_{ring} - A_1 (7.31)

= 0.011 – 0.00829

A_{fe} = 0.00302 m^2

Volume of the water flow $V_w = \frac{m_w}{\rho_w}$ (7.32)

$= \frac{0.0833}{999}$

$V_w = 8.34*10^{-5}$ m^3/ s

Velocity of water $v_w = \frac{V_w}{A_{fe}}$

$= \frac{8.34*10^{-5}}{0.00302}$

v_w = 0.0277 m/s

Prandtl number Pr = $(\frac{\rho_w * \eta_w * C_{pw}}{\lambda_w})$^0.33 (7.33)

$= (\frac{999*1.31*10^{-6}*4180}{0.0058})$^0.33

$= (937.94)^{0.33}$

Pr = 9.568

Reynolds number $$\mathrm{Re} = \left(\frac{(v_w * D)/1000}{\eta_w}\right)^{\wedge}0.65 \quad (7.34)$$

$$= \left(\frac{0.0277*22)/1000}{1.31*10^{-6}}\right\}^{\wedge}0.65$$

$$= (1.88*10^4)^{\wedge}0.65$$

$$\mathrm{Re} = 54.2727$$

Nusselt number $$\mathrm{Nu} = 0.26*\mathrm{Pr}*\mathrm{Re} \quad (7.35)$$

$$= 0.26*9.568*54.2727$$

$$\mathrm{Nu} = 135$$

Heat transfer coefficient $$\alpha_1 = \frac{\mathrm{Nu}*\lambda_w}{d/1000} \quad (7.36)$$

$$= \frac{135*0.0058}{20/1000}$$

$$\alpha_1 = 39.22 \text{ W}/m^2*\text{K}$$

Overall heat transfer coefficient $$K_1 = \frac{\pi}{(1/\alpha_1 D + \{(1/2\lambda_{cu})*\ln\frac{D}{d}\} + 1/\alpha_2 d} \quad (7.37)$$

$$= \frac{\pi}{(\frac{1}{39.22*22} + \left\{\left(\frac{1}{2*393}\right)*\ln\frac{22}{20}\right\} + \frac{1}{74.58*20}}$$

$$K_1 = 1.717 \text{ W/m*K}$$

Mean temperature difference of 1st cooler $\mathrm{MTD}_1 = 73.8°\mathrm{C}$

Total length of the tube $$L = \frac{Q_1}{K_1*\mathrm{MTD}_1} \quad (7.38)$$

$$= \frac{1021.23}{1.717*73.8}$$

$$L = 8.05 \text{ m}$$

Number of ring spirals $$N_s = \frac{L}{(L_{ring}/1000)} \quad (7.39)$$

$$= \frac{8.05}{377/1000}$$

$$N_s = 21.4$$

Length $$l = \frac{N_s * D}{1000} \tag{7.40}$$

$$= \frac{21.4 * 22}{1000}$$

$$l = 0.5 \text{ m}$$

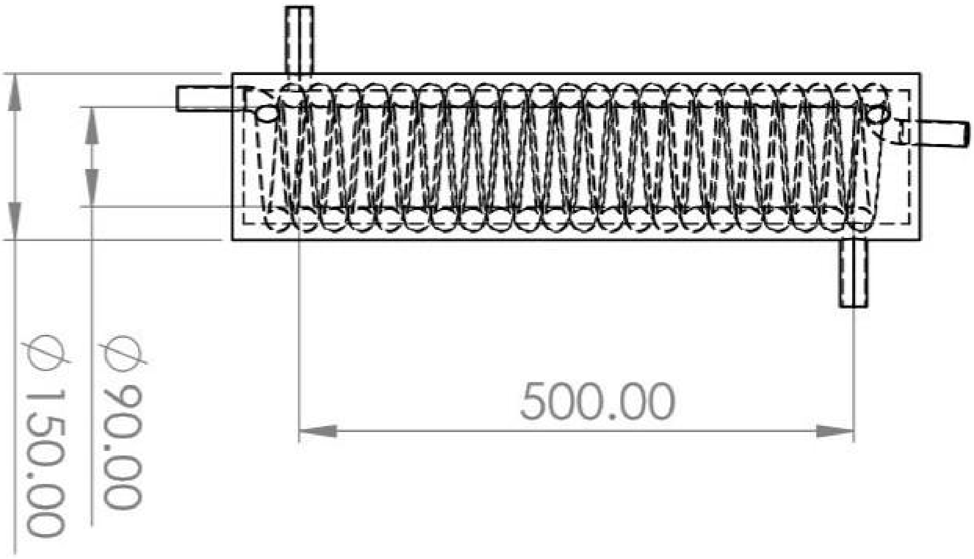

Figure 21 schematic view of 1st cooler

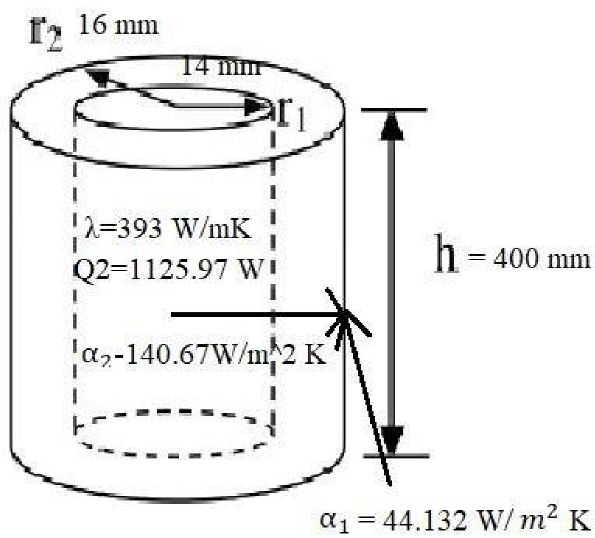

Figure 22 Heat transfer coefficient in copper tube of cooler II

Calculation of air flow section for 2nd cooler

Cooling power capacity Q_2 = 1125.97 W

Specific heat capacity C_{pair} = 1023 J/kg*K

Inlet temperature of air T_3 = 196.6 °C

Discharge air temperature of compressor $T^{|}$ = 30 °C

Average temperature $T_m = \frac{T_3 + T^{|}}{2}$

T_m = 113.3 °C

Pressure of the compressor p_3 = 3.420MPa

Thermal conductivity of air λ_{air} = 0.0307 W/m*K

Density of air ρ_{air} = 30.95 kg/m^3

Kinematic viscosity of air $\eta_{air} = 7.39 * 10^{-7}$

Dynamic viscosity of air $\mu_{air} = \rho_{air} * \eta_{air}$ (7.41)

$= 30.95 * 7.39 * 10^{-7}$

$\mu_{air} = 2.29 * 10^{-5}$ Pa*s

mass of the air flow m_{air} = 0.007 kg/s

Outer diameter of copper tube D = 16 mm

Inner diameter of copper tube d = 14 mm

Thermal conductivity of copper λ_{cu} = 393 W/m*K

Cross section of copper tube $A_{cu} = \frac{\{(d/1000)\ \hat{}2\} * 3.14}{4}$ (7.42)

$= \frac{\{(14/1000)\ \hat{}2\} * 3.14}{4}$

A_{cu} = 0.000154 m^2

Volume of the air flow $V_{air} = \frac{m_{air}}{\rho_{air}}$ (7.43)

$= \frac{0.007}{30.95}$

$V_{air} = 0.000213\ m^3/\ s$

Velocity of air $v_{\text{air}} = \frac{V_{air}}{A_{cu}}$ (7.44)

$= \frac{0.000213}{0.000154}$

$v_{\text{air}} = 1.387$ m/s

Prandtl number $\Pr = (\frac{\rho_{air}*\eta_{air}*C_{pair}}{\lambda_{air}})$^0.43 (7.45)

$= (\frac{30.95*7.39*10^{-7}*1023}{0.0307}$)^0.43

$= 0.7622^{0.43}$

Pr = 0.8898

Reynolds number $\text{Re} = (\frac{(v_{\text{air}}*d)/1000}{\eta_{air}}$)^0.8 (7.46)

$= (\frac{1.387*14)/1000}{7.39*10^{-7}}\}$^0.8

$= (2.63*10^4)$^0.8

Re = 3433.06 (7.47)

Nusselt number Nu = 0.021*Pr*Re

= 0.021*0.8898*3433.06

Nu = 64.1

Heat transfer coefficient $\alpha_2 = \frac{\text{Nu}*\ \lambda_{air}}{d/1000}$ (7.48)

$= \frac{64.1*\ 0.0307}{14/1000}$

$\alpha_2 = 140.67$ W/ m^2*K

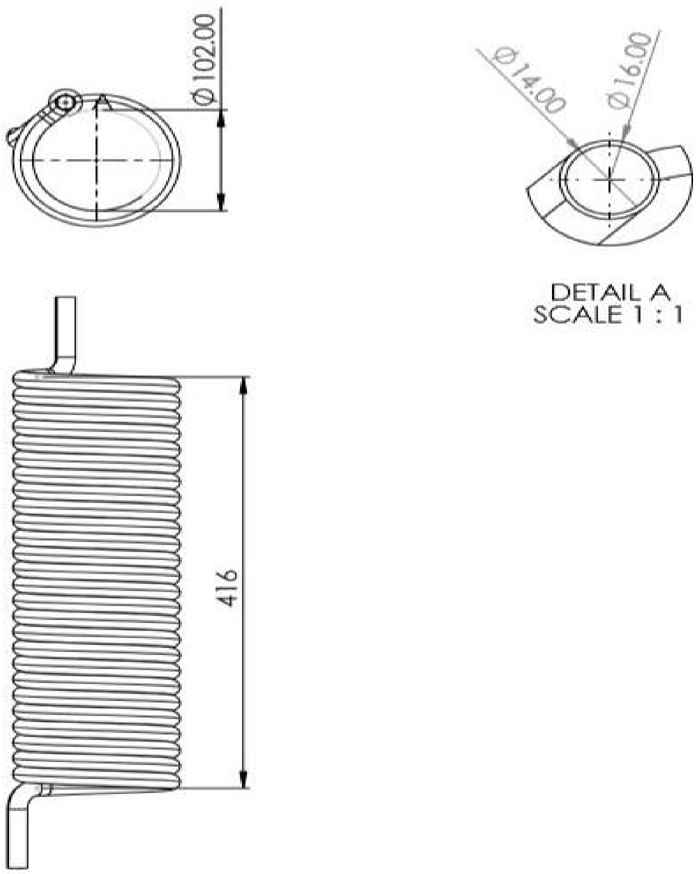

Figure 23 Schematic view of air flow tube in Cooler II

Calculation of Water flow section after 2nd cooler

Cooling power capacity Q_2 = 1125.97 W

Specific heat capacity C_{pw} = 4180 J/kg*K

Inlet temperature of cooler t_4 = 13.2 °C

Discharge temperature of cooler t_3 = 16.4 °C

Average temperature $T_m = \frac{t_3 + t_4}{2}$

T_m = 14.8 °C

Thermal conductivity of water λ_w = 0.0058 W/m*K

Density of water ρ_w = 999 kg/m^3

Kinematic viscosity of water $\eta_w = 1.31 * 10^{-6}$

Dynamic viscosity of water $\mu_w = \rho_w * \eta_w$ (7.49)

$= 999 * 1.31 * 10^{-6}$

$\mu_w = 1.30 * 10^{-3}$ Pa*s

mass of the water flow $m_w = 0.0833$ kg/s

Outer diameter of Iron tube $D_1 = 150$ mm

Inner diameter of Iron tube $D_2 = 102$ mm

Thickness of space $t = \frac{D_1 - D_2 - 2*D}{4}$ (7.50)

$= \frac{150-102-2*16}{4}$

$t = 4$mm

surface area of tubes $A_1 = \frac{(3.142 *(D_2+2*t+D)*D}{10^6}$ (7.51)

$= \frac{(3.142 *(102+2*4+16)*16}{10^6}$

$A_1 = 17.5\ m^2$

Cross section of outer diameter Iron tube $SD_1 = \frac{\{(D_1/1000)\ ^\wedge 2\} *3.14}{4}$ (7.52)

$= \frac{\{(150/1000)\ ^\wedge 2\} *3.14}{4}$

$SD_1 = 0.018\ m^2$

Cross section of inner diameter of iron tube $SD_2 = \frac{\{(D_2/1000)\ ^\wedge 2\} *3.14}{4}$ (7.53)

$= \frac{\{(102/1000)\ ^\wedge 2\} *3.14}{4}$

$SD_2 = 0.008\ m^2$

Surface area of ring $S_{ring} = SD_1 - SD_2$ (7.54)

$S_{ring} = 0.01$ mm

Length of the ring $L_{ring} = 3.14 *(D_1\text{-}2*t\text{-}D)$ (7.55)

$= 3.14 *(150\text{-}2*4\text{-}16)$

$L_{ring} = 395.9$ mm

Cross section of Iron tube $A_{fe} = S_{ring} - A_1$ (7.56)

$= 0.01 - 17.5$

$A_{fe} = 0.00317\ m^2$

Volume of the water flow $V_w = \frac{m_w}{\rho_w}$ (7.57)

$= \frac{0.0833}{999}$

$V_w = 8.34*10^{-5}\ m^3/\text{s}$

Velocity of water $v_w = \frac{V_w}{A_{fe}}$ (7.58)

$= \frac{8.34*10^{-5}}{0.00317}$

$v_w = 0.0263$ m/s

Prandtl number $\text{Pr} = (\frac{\rho_w*\eta_w*C_{pw}}{\lambda_w})$^0.33 (7.59)

$= (\frac{999*1.31*10^{-6}*4180}{0.0058})$^0.33

$= 937.94^{0.33}$

Pr = 9.568

Reynolds number $\text{Re} = (\frac{(v_w*D)/1000}{\eta_w})$^0.65 (7.60)

$$= (\frac{0.0263*16)/1000}{1.31*10^{-6}}\}\text{^}0.65$$

$$= (3.23*10^2)\text{^}0.65$$

$$Re = 42.7476$$

Nusselt number $\quad u = 0.26*Pr*Re \quad (7.61)$

$$= 0.26*9.568*42.7476$$

$$Nu = 106$$

Heat transfer coefficient $\quad \alpha_1 = \frac{Nu*\lambda_w}{d/1000} \quad (7.62)$

$$= \frac{106*0.0058}{14/1000}$$

$$\alpha_1 = 44.132 \text{ W}/m^2*K$$

Overall heat transfer coefficient $\quad K_2 = \frac{\pi}{(1/\alpha_1 D + \{(1/2\lambda_{cu})*\ln\frac{D}{d}\}+1/\alpha_2 d} \quad (7.63)$

$$= \frac{\pi}{(\frac{1}{44.132*16} + \left\{\left(\frac{1}{2*393}\right)*\ln\frac{16}{14}\right\} + \frac{1}{140.67*14}}$$

$$K_2 = 1.633 \text{ W/m*K}$$

Mean temperature difference of 2nd cooler $\quad MTD_2 = 68.9°C$

Total length of the tube $\quad L = \frac{Q_2}{K_2*MTD_1} \quad (7.64)$

$$= \frac{1125.97}{1.633*68.9}$$

$$L = 10 \text{ m}$$

Number of ring spirals $\quad N_s = \frac{L}{L_{ring}/1000} \quad (7.65)$

$$= \frac{10}{395.9/1000}$$

$$N_s = 25.3$$

Length $$l = \frac{N_s * D}{1000} \tag{7.66}$$

$$= \frac{25.3*16}{1000}$$

$$l = 0.4 \text{ m}$$

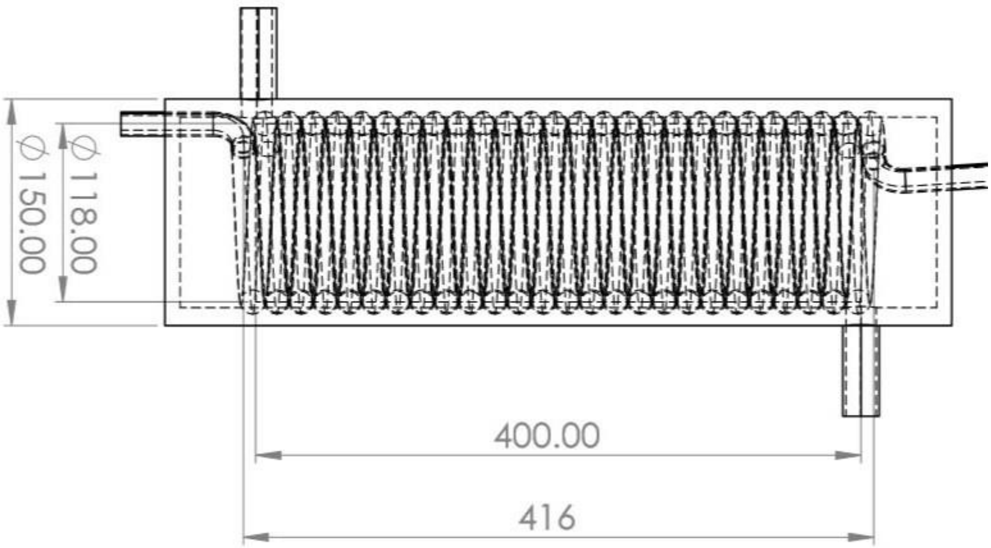

Figure 24 schematic view of 2nd cooler

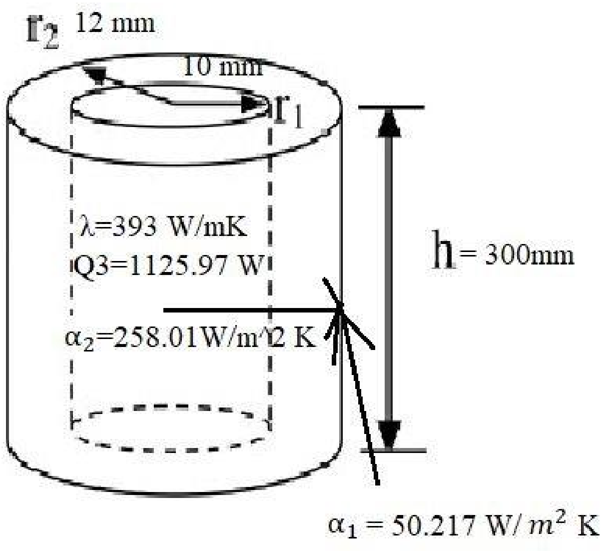

Figure 25 Heat transfer coefficient in copper tube of Aftercooler

Calculation of air flow section for After cooler

Cooling power capacity Q_3 = 1125.97 W

Specific heat capacity C_{pair} = 1023 J/kg*K

Inlet temperature of air T_4 = 196.6 °C

Discharge air temperature of compressor $T^{|}$ = 30 °C

Average temperature $T_m = \frac{T_4 + T^{|}}{2}$

T_m = 113.3 °C

Pressure of the compressor p_1 = 20MPa

Thermal conductivity of air λ_{air} = 0.0307 W/m*K

Density of air ρ_{air} = 181.05 kg/m^3

Kinematic viscosity of air $\eta_{air} = 1.26 * 10^{-7}$

Dynamic viscosity of air $\mu_{air} = \rho_{air} * \eta_{air}$ (7.67)

$= 181.05 * 1.26 * 10^{-7}$

$\mu_{air} = 2.28 * 10^{-5}$ Pa*s

mass of the air flow m_{air} = 0.007 kg/s

Outer diameter of copper tube D = 12 mm

Inner diameter of copper tube d = 10 mm

Thermal conductivity of copper λ_{cu} = 393 W/m*K

Cross section of copper tube $A_{cu} = \frac{\{(d/1000)\ \hat{}2\} * 3.14}{4}$ (7.68)

$= \frac{\{(10/1000)\ \hat{}2\} * 3.14}{4}$

A_{cu} = 0.0000785 m^2

Volume of the air flow $V_{air} = \frac{m_{air}}{\rho_{air}}$ (7.69)

$= \frac{0.007}{181.05}$

$V_{air} = 3.65 * 10^{-5}\ m^3/\ \mathrm{s}$

Velocity of air $v_{\mathrm{air}} = \frac{V_{air}}{\mathrm{A}_{cu}}$ (7.70)

$= \frac{3.65*10^{-5}}{0.0000785}$

$v_{\mathrm{air}} = 0.4648$ m/s

Prandtl number $\mathrm{Pr} = (\frac{\rho_{air}*\eta_{air}*C_{pair}}{\lambda_{air}})\text{^}0.43$ (7.71)

$= (\frac{181.05*1.26*10^{-7}*1023}{0.0307})\text{^}0.43$

$= 0.7602^{0.43}$

Pr = 0.8888

Reynolds number $\mathrm{Re} = (\frac{(v_{\mathrm{air}}*d)/1000}{\eta_{air}})\text{^}0.8$ (7.72)

$= (\frac{0.4648*10)/1000}{1.26*10^{-7}}\}\text{^}0.8$

$= (3.69*10^4)\text{^}0.8$

Re = 4502.903

Nusselt number Nu = 0.021*Pr*Re (7.73)

= 0.021*0.8888*4502.903

Nu = 84

Heat transfer coefficient $\alpha_2 = \frac{\mathrm{Nu}*\lambda_{air}}{d/1000}$ (7.74)

$= \frac{84*0.0307}{10/1000}$

$\alpha_2 = 258.01\ \mathrm{W}/\ m^2*\mathrm{K}$

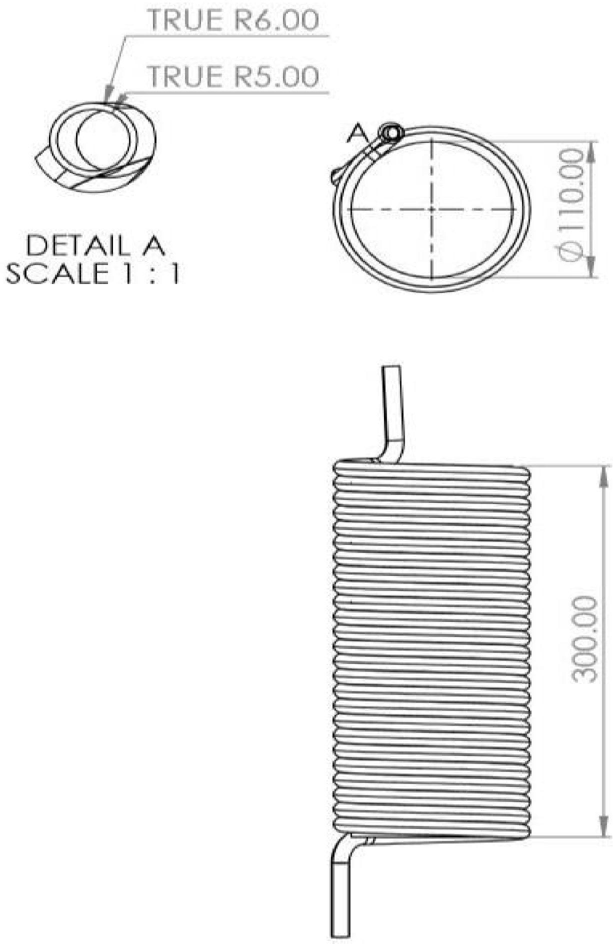

Figure 26 Schematic view of air flow tube in Aftercooler

Calculation of Water flow section After cooler

Cooling power capacity Q_3 = 1125.97 W

Specific heat capacity C_{pw} = 4180 J/kg*K

Inlet temperature of cooler t_2 = 9.9 °C

Discharge temperature of cooler t_4 = 13.2 °C

Average temperature $T_m = \frac{t_2 + t_4}{2}$

T_m = 11.5 °C

Thermal conductivity of water λ_w = 0.0058 W/m*K

Density of water ρ_w = 999 kg/m^3

Kinematic viscosity of water $\eta_w = 1.31 * 10^{-6}$

Dynamic viscosity of water $\mu_w = \rho_w * \eta_w$ (7.75)

$= 999*1.31 * 10^{-6}$

$\mu_w = 1.30 * 10^{-3}$ Pa*s

mass of the water flow $m_w = 0.0833$ kg/s

Outer diameter of Iron tube $D_1 = 150$ mm

Inner diameter of Iron tube $D_2 = 110$ mm

Thickness of space $t = \frac{D_1 - D_2 - 2*D}{4}$ (7.76)

$= \frac{150-110-2*12}{4}$

t = 4mm

surface area of tubes $A_1 = \frac{(3.142 *(D_2+2*t+ D) *D}{10^6}$ (7.77)

$= \frac{(3.142 *(110+2*4+12) *12}{10^6}$

$A_1 = 0.0049\ m^2$

Cross section of outer diameter Iron tube $SD_1 = \frac{\{(D_1/1000) \string^2\} *3.14}{4}$ (7.78)

$= \frac{\{(150/1000) \string^2\} *3.14}{4}$

$SD_1 = 0.018\ m^2$

Cross section of inner diameter of iron tube $SD_2 = \frac{\{(D_2/1000) \string^2\} *3.14}{4}$ (7.79)

$= \frac{\{(110/1000) \string^2\} *3.14}{4}$

$SD_2 = 0.01\ m^2$

Surface area of ring $S_{ring} = SD_1 - SD_2$ (7.80)

S_{ring} = 0.008 mm

Length of the ring L_{ring} = 3.14 *(D_1-2*t-D) (7.81)

= 3.14 *(150-2*4-12)

L_{ring} = 408.5 mm

Cross section of Iron tube $A_{fe} = S_{ring} - A_1$ (7.82)

= 0.008 – 0.0049

A_{fe} = 0.00327 m^2

Volume of the water flow $V_w = \frac{m_w}{\rho_w}$ (7.83)

$= \frac{0.0833}{999}$

$V_w = 8.34*10^{-5}$ m^3/ s

Velocity of water $v_w = \frac{V_w}{A_{fe}}$ (7.84)

$= \frac{8.34*10^{-5}}{0.00327}$

v_w = 0.0255 m/s

Prandtl number Pr = $(\frac{\rho_w*\eta_w*C_{pw}}{\lambda_w})$^0.33 (7.85)

$= (\frac{999*1.31*10^{-6}*4180}{0.0058})$^0.33

$= 937.94^{0.33}$

Pr = 9.568

Reynolds number $$\mathrm{Re} = (\frac{(v_w * D)/1000}{\eta_w})\text{^}0.65 \quad (7.86)$$

$$= (\frac{0.0255*12)/1000}{1.31*10^{-6}}\}\text{^}0.65$$

$$= (2.35*10^2)\text{^}0.65$$

$$\mathrm{Re} = 34.7440$$

Nusselt number $$\mathrm{Nu} = 0.26*\mathrm{Pr}*\mathrm{Re} \quad (7.87)$$

$$= 0.26*9.568*34.7440$$

$$\mathrm{Nu} = 86.4$$

Heat transfer coefficient $$\alpha_1 = \frac{\mathrm{Nu} * \lambda_w}{d/1000} \quad (7.88)$$

$$= \frac{86.4 * 0.0058}{10/1000}$$

$$\alpha_1 = 50.217 \text{ W}/ m^2 * \text{K}$$

Overall heat transfer coefficient $$\mathrm{K}_3 = \frac{\pi}{(1/\alpha_1 D + \{(1/2\lambda_{cu})*\ln\frac{D}{d}\}+1/\alpha_2 d} \quad (7.89)$$

$$= \frac{\pi}{(\frac{1}{50.217*12} + \left\{\left(\frac{1}{2*393}\right)*\ln\frac{12}{10}\right\} + \frac{1}{50.217*10}}$$

$$\mathrm{K}_3 = 1.535 \text{ W/m*K}$$

Mean temperature difference of $$\mathrm{MTD}_3 = 73.8°\mathrm{C}$$

Total length of the tube $$\mathrm{L} = \frac{\mathrm{Q}_3}{\mathrm{K}_3 * \mathrm{MTD}_1} \quad (7.90)$$

$$= \frac{1125.97}{1.535*73.8}$$

$$\mathrm{L} = 9.94 \text{ m}$$

Number of ring spirals $$\mathrm{N}_s = \frac{L}{L_{ring}/1000} \quad (7.91)$$

$$= \frac{9.94}{408.5/1000}$$

$$\mathrm{N}_s = 24.3$$

Length $$l = \frac{N_s * D}{1000} \tag{7.92}$$

$$= \frac{24.3 * 12}{1000}$$

$$l = 0.3 \text{ m}$$

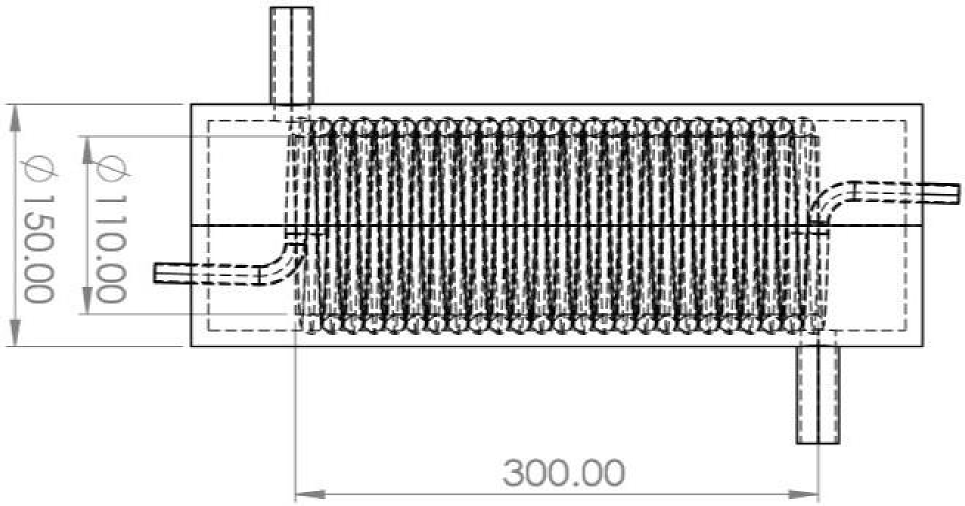

Figure 27 schematic view of Aftercooler.

8. Conclusion

The production of compressed air is very demanding on electricity consumption. Any increase in pressure above the required limit increases its energy demand for its production. Choosing the type of compressor, its performance and control has a significant impact on the reliability and cost of the entire process.

When the gas is compressed, its temperature rises, which adversely affects the function of the discharge valves, the lubrication deteriorates and the risk of oil ignition increases. Choosing the right cooling will reduce the work required to compress. The air-cooled chiller is able to cool the gas to temperatures only a few degrees above the ambient temperature. If the gas is to be cooler than the ambient temperature, water cooling is required.

With the help of flow meter instruments some of the parameters like pressure, temperature and mass of air flow inside the compressor is measured. Therefore, with these measurements and properties of air and water at respective pressure and temperature the dimensions of the both intercooler and aftercooler is calculated. The 3-D design model of heat exchangers with dimensions is designed in solid works vs software and attached in my thesis. The Copper material is selected for air flow pipe because it has high thermal conductivity and Iron material is selected for water flow pipe.

Therefore, to conclude a new design model of coolers is designed for piston compressor 1TSK 115, with calculated dimensions which helps to cool the air flow at each stage of compression and also increase in efficiency of the compressor.

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10. List of Annexes

Appendix A - Physical properties of air at 100 kPa

Appendix B - Physical properties of water

Appendix C - Three stage compressor calculation Excel

Appendix D - Calculation of density and kinematic viscosity of air.